The history and aesthetic development of bridges

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This chapter on the history and aesthetic development of bridges looks at the evolution and progress of bridges from their earliest conception by humans. Following a timeframe from the Palaeolithic period to the present all the various materials employed in construction are examined in relation bridge development. Aesthetic design in bridges – especially in the twentieth century is looked at in detail and the chapter ends with an essay on the search for aesthetic understanding in bridge design.

The early history of bridges

The age of timber and stone

The bridge has been a feature of human progress and evolution ever since the first hunter-gatherers became curious about the fertile land, animals and fruit flourishing on trees on the other side of a river or gorge. Early humans also had to devise ways to cross a stream and a deep gorge to survive. A boulder or two dropped into a shallow stream works well as a stepping stone, as many of us have discovered, but for deeper flowing streams a tree dropped between banks is a more successful solution. So the primitive idea of a simple beam bridge was born.

Today, in the forests of Peru and the foothills of the Himalayas, crude rope bridges span deep gorges and fast-flowing streams to maintain pathways from village to village for hill tribes. Such primitive rope bridges evolved from the vine and creeper that early humans would have used to swing through the forest and to cross a stream. Here is the second basic idea of a bridge – the suspension bridge.

For thousands of years during the Palaeolithic period, which lasted to around 8000 BC, we know that humans were living as nomads, hunting and gathering food. Slowly it dawned on early humans that following herds of deer or buffalo, or foraging for plant food haphazardly, could be better managed if the animals were kept in herds nearby and plants were grown and harvested in fields.

In this period the simple log bridge served many purposes. It needed to be sufficiently broad and strong to take cattle, a level and solid platform to transport food and other materials, as well as movable so that it could be withdrawn to prevent enemies from using it. Narrow tree trunk bridges were inadequate and were replaced by double log beams spaced wider apart on which short lengths of logs were placed and tied down to create a pathway. The pathways were planed by sharp scraping tools and any gaps between them plugged with branches and earth to create a level platform. For crossings over wide rivers, support piers were formed from piles of rocks in the stream. Sometimes stakes were driven into the riverbed to form a circle and then filled with stones, creating a crude cofferdam. Around 4000 BC, early Bronze Age ‘lake dwellers’ were living in timber houses built out over the lakes, in the area which is now Switzerland. To ensure their houses did not sink early, humans evolved ways to drive timber piles into the lake bed. From this discovery came the timber pile and the trestle bridge.

Primitive bridges were essentially post and lintel structures, either made from timber or stone or a combination of both. Sometime later, the simple rope and bamboo suspension bridge was devised; these developed into the rope suspension bridges that are in regular use today in the mountain reaches of China, Peru, Columbia, India and Nepal.

It took humans until 4000 BC to discover the secrets of arch construction. In the Tigris–Euphrates valley the Sumerians began building with adobe – a sun-dried mud brick – for their palaces, temples, ziggurats and city defences. Stone was not plentiful in this region and had to be imported from Persia, so it was used sparingly. The brick module dictated the construction principles they employed, to scale any height and to bridge any span. And through trial and error it was the arch and the barrel vault that was devised to build their monuments and grand architecture at the peak of their civilization. The ruins of the magnificent barrel-vaulted brick roof at Ptsephon and the Ishtar Gate at Babylon, are a reminder of Mesopotamian skill and craftsmanship. By the end of the Third Dynasty around 2475 BC, the Egyptians had also mastered the arch and used it frequently in constructing relieving arches and passageways for their temples and pyramids.

Without doubt, the arch is one of the greatest discoveries of humankind. The arch principle was the essential element in all building and bridge technology over later centuries. Its dynamic and expressive form gave rise to some of the greatest bridge structures ever built.

Earliest records of bridges

The earliest written record of a bridge appears to be a bridge built across the Euphrates around 600 BC as described by Herodotus, the fifth century Greek historian. The bridge linked the palaces of ancient Babylon on either side of the river. It had a hundred stone piers which supported wooden beams of cedar, cypress and palm to form a carriageway 35 ft wide and 600 ft long. Herodotus mentions that the floor of the bridge would be removed every night as a precaution against invaders.

In China it would appear that bridge building evolved at a faster pace than the ancient civilizations of Sumeria and Egypt. Records exist from the time of Emperor Yoa in 2300 BC on the traditions of bridge building. Early Chinese bridges included pontoons or floating bridges and probably looked like the primitive pontoon bridges built in China today. Boats called sampans about 30 ft long were anchored side by side in the direction of the current and then bridged by a walkway. The other bridge forms were the simple post and lintel beam, the cantilever beam and rope suspension cradles. Timber beam bridges, like those of Europe, were often supported on rows of timber piles of soft fir wood called ‘foochow poles’, so called because they were grown in Foochow. A team of builders would hammer the poles into the riverbed using a cylindrical stone fitted with bamboo handles. A short crosspiece was fixed between pairs of poles to form the supports that would carry timber boards which were then covered in clay to form the pathway over the river.

In later centuries Chinese bridge building was dominated by the arch, which they copied and adapted from the Middle East as they travelled the silk routes which opened during the Han Dynasty around 100 AD.

Through Herodotus we learn about the Persian ruler Xerxes and the vast pontoon bridge he built, consisting of two parallel rows of 360 boats, tied to each other and to the bank and anchored to the bed of the Hellespont, which is the Dardanelles today. Xerxes wanted to get his army of two million men and horses to the other bank to meet the Greeks at Thermophalae. It took seven days and seven nights to get the army across the river. Sadly for Xerxes, his massive army was defeated at the Battle of Thermophalae in 480 BC, the remnants of which retreated back over the pontoon bridge to fight another day. The Persians were great bridge builders and built many arch, cantilever and beam bridges. There is a bridge still standing in Khuzistan at Dizful over the river Diz which could date anywhere from 350 BC to 400 AD. The bridge consists of 20 voussoir arches which are slightly pointed and has a total length of 1250 ft. Above the level of the arch springing are small spandrel arches, semicircular in length, which give the entire bridge an Islamic look, hence the uncertainty of its Persian origins.

The Greeks did not do much bridge building over their illustrious history, being a seafaring nation that lived on self-contained islands and in feudal groups scattered across the Mediterranean. They exclusively used post and lintel construction in evolving a classical order in their architecture, and built some of the most breathtaking temples, monuments and cities the world has ever seen, such as the Parthenon, the Temple of Zeus, the cities of Ephesus, Miletus and Delphi, to name but a few. They were quite capable of building arches like their forbears the Etruscans when necessary. There are examples of Greek voussoir arch construction that compare with the Beehive Tomb at Mycenea, such as the ruins of an arch bridge with a 27 ft span at Pergamon in Turkey.

The Romans

The Romans on the other hand were the masters of practical building skills. They were a nation of builders who took arch construction to a science and high art form during their domination of Mediterranean Europe. Their influence on bridge building technology and architecture has been profound. They conquered the world as it was then known, built roadways, canals and cities that linked Europe to Asia and North Africa and produced the first true bridge engineers in the history of humankind. The Romans understood that the establishment and maintenance of their empire depended on efficient and permanent communications. Building roads and bridges was therefore a high priority.

The Romans also realised, as did the Chinese in later centuries, that timber structures, particularly those embedded in water, had a short life, were prone to decay, insect infestation and fire hazards. Prestigious buildings and important bridge structures were therefore built of stone. But the Romans had also learnt to preserve their timber structures by soaking timber in oil and resin as a protection against dry rot, and coating them with alum for fireproofing. They learnt that hardwood was more durable than softwoods, and that oak was best for sub-structure work in the ground, alder for piles in water; while fir, cypress and cedar were best for the superstructure above ground.

They understood the different qualities of the stone that they quarried. Tufa, a yellow volcanic stone, was good in compression but had to be protected from weathering by stucco – a lime wash. Travertine was harder and more durable and could be left exposed, but was not very fire resistant. The most durable materials such as marble had to be imported from distant regions of Greece and even as far away as Egypt and Asia Minor (Turkey). The Romans’ big breakthrough in material science was the discovery of lime mortar and pozzolanic cement, which was based on the volcanic clay that was found in the village of Puzzoli. They used it as mortar for laying bricks or stones and often mixed it with burnt lime and stones to create a waterproof concrete.

The Romans realised that voussoir arches could span further than any unsupported stone beam, and would be more durable and robust than any other structure. Semi-circular arches were always built by the Romans, with the thrust from the arch going directly down on to the support pier. This meant that piers had to be large. If they were built wide enough at about one-third of the arch span, then any two piers could support an arch without shoring or propping from the sides. In this way it was possible to build a bridge from shore to shore, a span at a time, without having to form the entire substructure across the river before starting the arches. They developed a method of constructing the foundation on the riverbed within a cofferdam or watertight dry enclosure, formed by a double ring of timber piles with clay packed into the gap between them to act as a water seal. The water inside the cofferdam was then pumped out and the foundation substructure was then built within it. The massive piers often restricted the width of the river channel, increasing the speed of flow past the piers and increasing the scour action. To counter this, the piers were built with cutwaters, which were pointed to cleave the water so it would not scour the foundations.

The stone arch was built on a wooden framework built out from the piers and known as centring. The top surface was shaped to the exact semicircular profile of the arch. Parallel arches of stones were placed side by side to create the full width of the roadway. The semicircular arch meant that all the stones were cut identically and that no mortar was needed to bind them together once the keystone was locked into position. The compression forces in the arch ensured complete stability of the span. The Romans did build many timber bridges, but they have not stood the test of time, and today all that remains of their achievement after 2000 years are a handful of stone bridges in Rome, and a few scattered examples in France (see **Figure 1**), Spain, North Africa, Turkey and other former Roman colonies. But what still stands today, be it bridges or aqueducts, rank among the most inspiring and noble of bridge structures ever built, considering the limitations of their technology.

The Dark Ages and the brothers of the bridge

When the Roman Empire collapsed it seemed that the light of progress around the world went out for a long while. The Huns, the Visigoths, Saxons, Mongols and Danes did little building in their raids across Europe and Asia to plunder and destroy. It was left to the spread of Christianity and the strength of the Church to start the next boom in road building and bridge building around 1000 AD.

It was the Church that had preserved and developed both spiritual understanding and the practical knowledge of

Figure 1 Pont du Gard, Nîmes

building during this period. And not surprisingly it was bridge building among the many skills and crafts that became associated with it.

A group of friars of the Altopascio order near Lucca in northern Italy lived in a large dwelling called the Hospice of St James. The friars were skilled at carpentry and masonry, having built their own priory and no doubt helped with others. The surrounding countryside was wild and dangerous, and the refuge they built was a popular resting place for pilgrims and travellers using the ancient road from Tuscany to Rome. In 1244 Emperor Frederick II required that the hospice build a proper bridge across the White Arno for pilgrims and travellers. With their skills and practical knowledge the friars set up a cooperative to build the bridge. After completing the bridge over the White Arno their fame spread through Italy and France. It sparked off an interest in bridge building among other ecclesiastical orders. In France, a group of Benedictine monks established the religious order of the Frères Pontiffs (brothers of the bridge) to build a bridge over the Durance.

And so the 'brothers of the bridge' order became established among Benedictine monks and spread from France to England by the thirteenth century. The purpose of the order, apart from its spiritual duties, was to aid travellers and pilgrims, to build bridges along pilgrimage routes or to establish boats for their use and to receive them in hospices built for them on the bank. The brothers of the bridge were great teachers, who strove to emulate and continue the magnificent work of the Roman bridge builders.

The most famous and legendary bridge of this period was built by the Order of the Saint Jacques du Haut Pas, whose great hospice once stood on the banks of the Seine in Paris on the site of the present church of that name. They built the Pont Esprit over the Rhône but their masterpiece was the neighbouring bridge at Avignon. It was truly a magnificent and record-breaking achievement for its time. Its beauty has inspired writers, poets and musicians over the centuries. Sadly all that remains today at Avignon are

Figure 2 Old London Bridge

just four out of the 20 spans of the bridge and the chapel where the supposed creator of the bridge was interred and later canonised as Saint Benezet.

While Pont d'Avignon was being built in France, another monk of the Benedictine order in England, Peter of Colechurch, was planning the building of the first masonry bridge over the Thames. A campaign for funds was launched with enthusiasm; it was not only the rich town people, the merchants and money lenders who made generous donations, but also the common people of London all gave freely. Until the sixteenth century a list of donors could be seen hanging in the chapel on the bridge. The structure that was built in 1206 was Old London Bridge (see **Figure 2**) and ranks after Pont d'Avignon in fame. It was such a popular bridge that buildings and warehouses were soon erected on it. It became so fashionable a location that the young noblemen of Queen Elizabeth's household resided in a curious four-storey timber building imported piece by piece from the Netherlands, called the Nonesuch House.

Towns continued to sponsor and promote the building of stronger and better bridges and roads. They did not always get the brothers of the bridge to build them, because they were often committed to other projects for many years in advance. Instead, guilds of master masons and carpenters were formed and spread across Europe offering their services. Even government officials were united in this community enterprise and began to grasp the initiative and drive for better road and bridge networks across the country (**Figure 3** shows an example of a medieval fortified bridge). Soon the vestiges of the Dark Ages and feudalism were transformed to the age of enlightenment and the Renaissance. The Ponte de Vecchio in Florence, built towards the end of this period, marks the turning-point of the Dark Ages. It was a covered bridge erected in 1345, lined with jewellery shops and galleries, with an upper passageway added later, that was a link between the royal and government palaces, the Uffizi and Pitti Palaces. The piers, which are 20 ft thick, support the overhanging building as well as the bridge spans. The most innovative features of the bridge are the arch spans which are extremely shallow compared with any previous arches ever built or indeed many contemporary European bridges. It was built as a

Figure 3 Monmow Bridge, Monmouth – an example of a medieval fortified bridge

segmental arch, which is unusual for bridge builders of that period because they could not possibly have determined the thrust from the arches mathematically with the level of knowledge they possessed. How they achieved this is not known (as is also the case for the segmental arches of Pont d'Avignon). The architect of this radical design was Taddeo Gaddi, who had studied under the great painter Giotto, and was regarded as one of the great names of the Italian Renaissance that followed.

The Renaissance

Not since the days of Homer, Aristotle and Archimedes in Hellenistic times have such great feats of discovery in science and mathematics, and such works of art and architecture been achieved, as during the Renaissance. Modern science was born in this period through the enquiring genius of Copernicus, Da Vinci, Francis Bacon and Galileo, and in art and architecture through Michelangelo, Brunellesci and Palladio. During the Renaissance there was a continual search for the truth, explanations of natural phenomena, greater self-awareness and rigorous analysis of Greek and Roman culture. As far as bridge building was concerned, particularly in Italy, it was regarded as a high art form. Much emphasis was placed on decorative order and pleasing proportions as well as the stability and permanence of its construction. Bridge design was architect driven for the first time, with Da Vinci, Palladio, Brunelleschi and even Michelangelo all experimenting with the possibilities of new bridge forms. The most significant contribution of the Renaissance was the invention of the truss system, developed by Palladio from the simple king post and queen post roof truss, and the founding of the science of structural analysis with the first book ever written on the subject by Galileo Galilei entitled *Dialoghi delle Nuove Scienze* (*Dialogues on the New Science*), published in 1638.

Palladio did not build many bridges in his lifetime; many of his truss bridge ideas were considered too daring and radical and his work lay forgotten until the eighteenth century. His great treatise published in 1520 *Four Books of Architecture* in which he applied four different truss systems for building bridges, was destined to influence bridge builders in future years when the truss replaced the arch as the principal form of construction. Bridge builders during the Renaissance were clever material technologists who were preoccupied with the art of bridge construction and how they could build with less labour and materials. It was a time of inflation when the price of building materials and labour was escalating. The most famous bridge builders in this era were Amannati, Da Ponte, and Du Cerceau.

Which Renaissance bridge is the most beautiful: Florence's Santa Trinita, Venice's Rialto or Paris' Pont Neuf? Arguably the most famous and celebrated bridge of the Renaissance was the Rialto bridge designed by Antonio Da Ponte in Venice.

John Ruskin said of the Rialto: 'The best building raised in the time of the Grotesque Renaissance, very noble in its simplicity, in its proportions and its masonry.' Its designer was 75 years old when he won the contract to build the Rialto, and was 79 when it was finished. It was a single segmental arch span of 87 ft 7 in, which rises 25 ft 11 in at the crown. The bridge is 75 ft 3 in wide, with a central roadway, shops on both sides and two small paths on the outside, next to the parapets. Two sets of arches, six each of the large central arch, support the roof and enclose the 24 shops within it. It took three and half years to build and kept all the stone masons in the city fully occupied in work for two of those years.

Equally innovative and skilful bridge construction was progressing across Europe. In the state of Bohemia across the Moldau at Prague was built the longest bridge over water, the Karlsbrucke in 1503, and the most monumental and imperial bridge of the Renaissance. It took a century and half to completely finish. It was adorned with statues of saints and martyrs and terminates on each bank with an imposing tower gateway. In France at this time a fine example of the early French Renaissance, the Pont Neuf, was being designed (**Figure 4**). It was the second stone bridge to be built in Paris and although its design and construction did not represent a great leap forward in bridge building, it occupies a special place in Parisian hearts. Designed by Jacques Androuet Du Cerceau, the two arms of the Pont Neuf that join the Ille de la Cité to the left and right bank was a massive undertaking. Although all the arches are semicircular and not segmental, no two spans are alike, as they vary from 31 to 61 ft in span and also differ on the downstream and upstream sides of each arch and were built on a skew of 10%. Du Cerceau wanted the bridge to be a true unencumbered thoroughfare bereft of any houses and shops. But the people of Paris demanded shops and houses which resulted in modification to the few short-span piers that had been constructed.

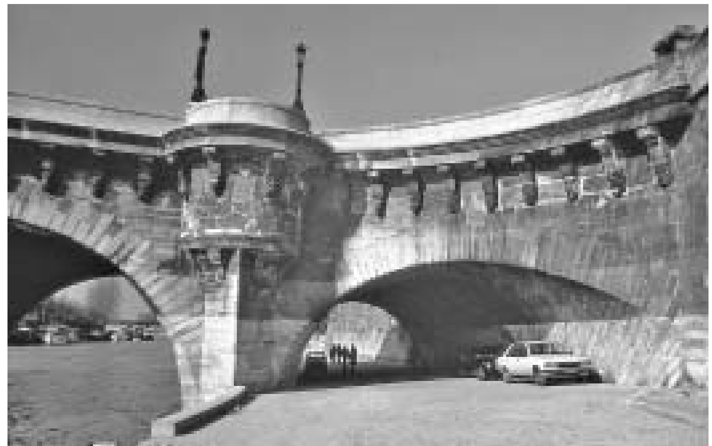

Figure 4 Pont Neuf, Paris (courtesy of JL Michotey)

The Pont Neuf has stood now for 400 years and was the centre of trade and the principal access to and from the crowded island when it was built. The booths and stalls on the bridge became so popular that all sorts of traders used it including booksellers, pastry cooks, jugglers and peddlers. They crowded the roadway until there were some 200 stalls and booths packed into every niche along the pavement. The longer left bank of the Pont Neuf was extensively reconstructed in 1850 to exactly the same details, after many years of repairs and attention to its poor foundations. The right bank with the shorter spans has been left intact. The entire bridge has been cleared of all stalls and booths and is used today as a road bridge.

The finest examples of late French Renaissance bridges built during the seventeenth century are the Pont Royale and Pont Marie bridges, both of which are still standing today. The Pont Royale (**Figure 5**) was the first bridge in Paris to feature elliptical arches and the first to use an

Figure 5 Pont Royale, Paris (courtesy of J Crossley)

open caisson to provide a dry working area in the riverbed. The foundations for the bridge piers were designed and constructed under the supervision of Francosi Romain, a preaching brother from the Netherlands who was an expert in solving difficult foundation problems. Both the bridge architect François Mansart and the builder Jacques Gabriel called on Romain after they ran into foundation problems. Romain introduced dredging in the preparation of the riverbed for the caisson using a machine that he had developed. After excavations were finished the caisson was sunk to the bed, but the top was kept above the water level. The water was then pumped out and the masonry work of the pier was then built inside the dry chamber. The five arch spans of the Pont Royale increase in span towards the centre and, although it has practically no ornamentation, it blends beautifully into its river setting and the bankside environment.

The Renaissance brought improvements in both the art and science of bridge building. For the first time bridges began to be regarded as civic works of art. The master bridge builder had to be an architect, structural theorist and practical builder, all rolled into one. The bridge that was without doubt the finest exhibition of engineering skills in this era was the slender elliptical arched bridge of Santa Trinita in Florence, designed by Bartholomae Ammannati in 1567. Many scholars are still mystified to this day as to how Ammannati arrived at such pleasing, slender curves to the arches.

Eighteenth-century bridge building

The Age of Reason

In this period, masonry arch construction reached perfection, due to a momentous discovery by Perronet and the innovative construction techniques of John Rennie. Just as the masonry arch reached its zenith 7000 years after the first crude corbelled arch in Mesopotamia, it was to be threatened by a new building material – iron – and the timber truss, as the principal construction for bridges in the future.

This was the era when civil engineering as a profession was born, when the first school of engineering was established in Paris at the Ecole de Paris during the reign of Louis XV. The director of the school was Gabriel who had designed the Pont Royal. He was given the responsibility of collecting and assimilating all the scientific information and knowledge there was on the science and history of bridges, buildings, roads and canals.

With such a vast bank of collective knowledge it was inevitable that building architecture and civil engineering should be separated into the two fields of expertise. It was suggested it was not possible for one man in his brief life to master the essentials of both subjects. Moreover, it also became clear that the broad education received in civil engineering at the Corps des Ponts et Chaussées at the Ecole de Paris was not sufficient for the engineering of bridge projects. More specialised training was needed in bridge engineering. In 1747 the first school of bridge engineering was founded in Paris at the historic Ecole des Ponts et Chaussées. The founder of the school was Trudiane, and the first teacher and director was a brilliant young engineer named Jean Perronet.

Jean Perronet has been called the father of modern bridge engineering for his inventive genius and design of the greatest masonry arch bridges of that century. In his hands the masonry arch reached perfection. The arch he chose was the curve of a segment of a circle of larger radius, instead of the familiar three-centred arch. To express the slenderness of the arch he raised the haunch of the arch considerably above the piers. He was the first person to realise that the horizontal thrust of the arch was carried through the spans to the abutments and that the piers, in addition to carrying the vertical load, also had to resist the difference between the thrusts of the adjacent spans. He deduced that if the arch spans were about equal and all the arches were in place before the centring was removed, the piers could be greatly reduced in size.

What remains of Perronet's great work? Only his last bridge, the glorious Pont de la Concorde in Paris, built when he was in his eighties. It is one of the most slender and daring stone arch bridges ever built in the world. 'Even with modern analysis', suggests Professor James Finch, author of *Engineering and Western Civilisation*, 'we could not further refine Perronet's design.'

With France under the inspired leadership of Gabriel and then Perronet, the rest of Europe could only admire and copy these great advances in bridge building. In England, a young Scotsman, John Rennie, was making his mark following in the footsteps of the great French engineers. He was regarded as the natural successor to Perronet, who was a very old man when Rennie started his career. Rennie was a brilliant mathematician, a mechanical genius and pioneering civil engineer. In his early years he worked for James Watt to build the first steam-powered grinding mills at Abbey Mills in London, and later designed canals and drainage systems to drain the marshy fens of Lincolnshire. He built his first bridge in 1779 across the Tweed at Kelso. It was a modest affair with a pier width-to-span ratio of one to six with a conservative elliptical arch span. He picked up the theory of bridge design from textbooks and from studies and discussion about arches and voussoirs with his mentor Dr Robison of Edinburgh University. He designed bridges with a flat, level roadway rather than the characteristic hump of most English bridges. It was a radical departure from convention and his bridges were much admired by all the town's people, farmers and traders who transported material and cattle

Figure 6 John Rennie's New London Bridge – under construction

across them. The first bridge at Kelso was a modest forerunner to the many famous bridges that Rennie went on to build, namely Waterloo, Southwark and New London Bridge (**Figure 6**). What then was Rennie's contribution to bridge building? For Waterloo Bridge, the centring for the arches was assembled on the shore then floated out on barges into position. So well and efficiently did this system work that the framework for each span could be put into position in a week. This was a fast erection speed and as a result Rennie was able to halve bridge construction time. So soundly were Rennie's bridges built that 40 years later Waterloo Bridge had settled only 5 in. Rennie's semi-elliptical arches, sound engineering methods and rapid assembly technique, together with the Perronet segmental arch, divided pier and understanding of arch thrust, changed bridge design theory for all time.

The carpenter bridges

The USA, with its vast expansion of roads and waterways, following in the wake of commercial growth in the eighteenth century, was to become the home of the timber bridge in the nineteenth century.

The USA had no tradition or history of building with stone, and so early bridge builders used the most plentiful and economical materials that were available: timber. The Americans produced some of the most remarkable timber bridge structures ever seen, but they were not the first to pioneer such structures. The Grubenmann brothers of Switzerland were the first to design quasi-timber truss bridges in the eighteenth century. The Wettingen Bridge over the Limmat just west of Zürich was considered their finest work. The bridge combines the arch and truss principle with seven oak beams bound close together to form a catenary arch to which a timber truss was fixed. The span of the Wettingen was 309 ft and far exceeded any other timber bridge span.

Of course, there were numerous timber beam and trestle bridges built in Europe and the USA. However, in order to bridge deep gorges, broad rivers and boggy estuaries such as those that ran through North America and support the heavy loads of chuck wagons and cattle, something more robust was needed. The answer according to the Grubenmanns was a timber truss arch bridge, but it was not a true truss.

Palmer, Wernwag and Burr, the so-called American carpenter bridge builders, designed more by intuition than by calculation and developed the truss arch to span further than any other wooden construction. This was the third and last of the three basic bridge forms to be discovered. The first person who made the truss arch bridge a success in the USA and who patented his truss design was Timothy Palmer. In 1792 Palmer built a bridge consisting of two trussed arches over the Merrimac; it looked very like one of Palladio's truss designs, except the arch was the dominant supporting structure. His 'Permanent Bridge' over the Schuylkill built in 1806 was his most celebrated. When the bridge was finished the president of the bridge company suggested that it would be a good idea to cover the bridge to preserve the timber from rot and decay in the future. Palmer went further than that and timbered the sides as well, completely enclosing the bridge. Thus, America's distinctive covered bridge was established. By enclosing the bridge it stopped snow getting in and piling up on the deck, causing it to collapse from the extra load.

Wernwag was a German immigrant from Pennsylvania, who built 29 truss-type bridges in his lifetime. His designs integrated the arch and truss into one composite structure rather more successfully than Palmer's. Wernwag's famous bridge was the Collossus over the Schuylkill just upstream from Palmer's 'Permanent Bridge' and was composed of two pairs of parallel arches, linked by a framing truss, which carried the roadway. The truss itself was acting as bracing reinforcement and consisted of heavy verticals and light diagonals. The diagonal elements were remarkable because they were iron rods, and were the first iron rods to be used in a long-span bridge. In its day the Collossus was the longest wooden bridge in the USA, having a clear span of 304 ft. Fire destroyed the bridge in 1838. It was later replaced by Charles Ellet's pioneering suspension bridge.

Theodore Burr was the most famous of the illustrious triumvirate. Burr developed a timber truss design based on the simple king and queen post truss of Palladio. He came closest to building the first true truss bridge; however, it proved unstable under moving loads. Burr then strengthened the truss with an arch. It was significant that here the arch was added to the truss rather than the other way round. Burr arch-trusses were quick to assemble and modest in cost to build, and for a time they were the most popular timber bridge form in the USA.

By 1820 the truss principle had been well explored and although the design theory was not understood in practice it had been tested to the limit. It was left to Ithiel Town to develop and build the first true truss bridge, which he patented and called the Town Lattice. It was a true truss because it was free from arch action and any horizontal thrust. It was so simple to build that it could be nailed together in a few days and cost next to nothing compared to other alternatives. Town promoted his timber structure with the slogan 'built by the mile and cut by the yard'. He didn't build the Town Lattice truss bridges himself, but issued licences to local builders to use his patent design instead. He collected a dollar for every foot built and two if a bridge was built without his permission. By doubling the planking and wooden pins to fasten the structure together Town made his truss carry the early railroads.

The railroad and the truss bridge

With arrival of the railways in the USA, bridge building continued to develop in two separate ways. One school continued to evolve stronger and leaner timber truss structures while the other experimented with cast iron and wrought iron, slowly replacing timber as the principal construction material.

The first patent truss to incorporate iron into a timber structure was the Howe Truss. It had top and bottom chords and diagonal bracing in timber and vertical members of iron rod in tension. This basic design, with modifications, continued right into the next century. The first fully designed truss was the Pratt Truss which reversed the forces of the Howe Truss by putting the vertical timber members in compression and the iron diagonal members in tension. The Whipple truss in 1847 was the first all-iron truss – a bowstring truss – with the top chord and vertical compression members made from cast iron and the bottom chord and diagonal bracing members made from wrought iron. Later Fink, Bollman, Bow and Haupt in the USA, along with Cullman and Warren in Europe, developed the truss to a fine art, incorporating wire-strand cable, timber and iron to form lightweight but strong bridges that could carry railways. **Figures 7** and **8** show examples of various truss types.

The stresses and fatigue loading from moving trains in the late nineteenth century caused catastrophic failure of many timber truss and many iron truss bridges. The world was horrified by the tragedy and death toll from collapsing bridges. At one stage as many as one bridge in every four used by the railway network in the USA had a serious defect or had collapsed. By the turn of the century the iron truss railway bridges had been replaced by stronger and more durable structures. Design codes and safety regulations were drawn up and professional associations were incorporated to train, regulate and monitor the quality of bridge engineers.

Figure 7 Example of the Bollman truss, Central Park Bridge (courtesy of E Deloney)

In the nineteenth century the truss, the last of the three principal bridge forms, had at long last been discovered. With the coming of the industrial revolution, and the rapid growth of the machine age – dominated by the railway and motor car – a huge burden was placed on civil engineering, material technology and bridge building. Many new and daring ideas were tried and tested, and many innovative bridge forms were built. There were some spectacular failures. As many as seven major new bridge types were to emerge during this period: the box girder, the cantilever truss girder, the reinforced and prestressed concrete arch, the steel arch, glued segmental construction, cable-stayed bridges and stressed ribbon bridges.

The past 200 years: bridge development in the nineteenth and twentieth centuries

The industrial revolution which began in Britain at the end of the eighteenth century, gradually spread and brought with it huge changes in all aspects of everyday life. New forms of bulk transportation, by canal and rail, were developed to keep pace with the increasing exploitation of coal and the manufacture of textiles and pottery. Coal fuelled the hot furnaces to provide the high temperatures to smelt iron. Henry Bessemer invented a method to

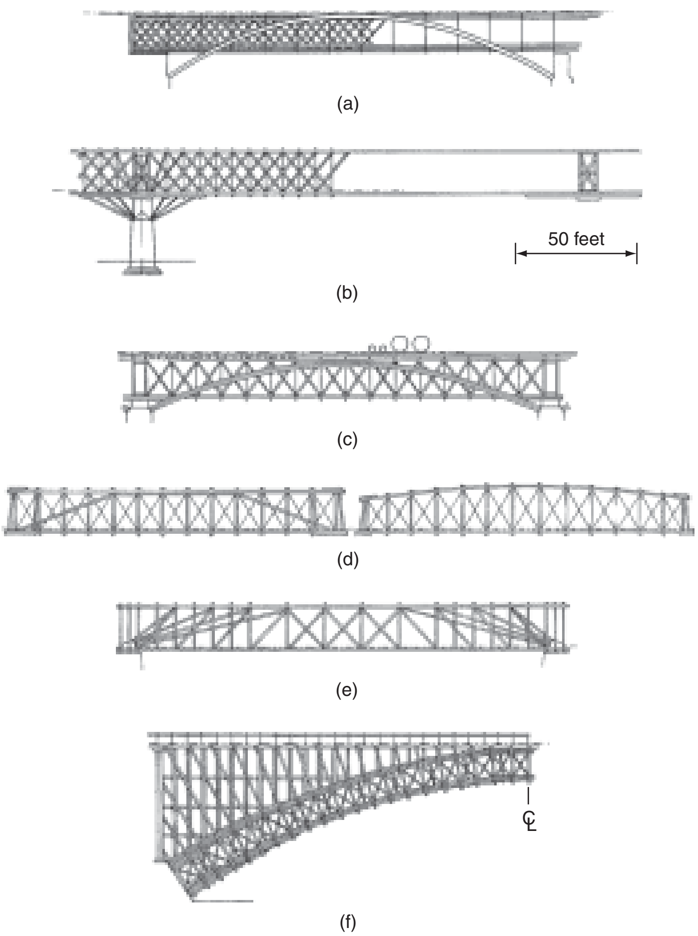

Figure 8 US patent truss types: (a) 1839 Wilton; (b) 1844 Howe; (c) 1849 Stone-Howe; (d) 1844 Pratt; (e) 1846 Hassard; (f) 1848 Adams

produce crude steel alloy by blowing hot air over smelted iron. Seimens and Martins refined this process further to produce the low-carbon steels of today. High temperature was also essential in the production of cement which Joseph Aspdin discovered by burning limestone and clay on his kitchen stove in Leeds in 1824. Wood and stone were gradually replaced by cast iron and wrought iron construction, which in turn was replaced by first steel and then concrete – the two primary materials of bridge building in the twentieth century.

Growing towns and expanding cities demanded continuous improvement and extension of the road, canal and railway infrastructure. The machine age introduced the steam engine, the internal combustion engine, factory production lines, domestic appliances, electricity, gas, processed food and the tractor. Faster assembly of bridges was essential, and this meant prefabricating lightweight, but tough, bridge components. The heavy steam engines and longer goods train imposed larger stresses on bridge structures than ever before. Bridges had to be stronger and more rigid in construction and yet had to be faster to assemble to keep pace with progress. Connections had to be stronger and more efficient. The nut and bolt was replaced by the rivet, which was replaced by the high-strength friction grip bolt and the welded connection.

When the automobile arrived it resulted in a road network that eventually criss-crossed the entire countryside from town to city, over mountain ranges, valleys, streams, rivers, estuaries and seas. Even bigger and better bridges were now needed to connect islands to the mainland and countries to continents in order to open up major trading routes. The continuous search and development for high-strength materials of steel, concrete, carbon fibre and aramids today combined with sophisticated computer analysis and dynamic testing of bridge structures against earthquakes, hurricane wind and tidal flows has enabled bridges to span even further. In the last two centuries bridge spans have leapt from 350 ft to over 6000 ft. This is the age of the mighty suspension bridges, the elegant cable-stayed bridges, the steel arch truss, the glued segmental and cantilever box girder bridges.

The key events and achievements of this large output of bridge building are briefly summarised to illustrate the rapid pace of change and many bridge ideas that were advanced. In the past two centuries more bridges were built than in the entire history of bridge building prior to that!

The age of iron (1775–1880)

Of all the materials used in bridge construction – stone, wood, brick, steel and concrete – iron was used for the shortest time. Cast iron was first smelted from iron ore successfully by Dud Dudley in 1619. It was another century before Abraham Derby devised a method to economically smelt iron in large quantities. However, the brittle quality of cast iron made it safe to use only in compression in the form of an arch. Wrought iron, which replaced cast iron many years later, was a ductile material that could carry tension. It was produced in large quantities after 1783 when Henry Cort developed a puddling furnace process to drive impurities out of pig iron.

But iron bridges suffered some of the worst failures and disasters in the history of bridge building. The vibration and dynamic loading from a heavy steam locomotive and from goods wagons, create cyclic stress patterns on the bridge structure as the wheels roll over the bridge, going from zero load to full load then back to zero. Over a period of time these stress patterns can lead to brittle failure and fatigue in cast iron and wrought iron. In one year alone in the USA, as many as one in every four iron and timber bridges had suffered a serious flaw or had collapsed. Rigorous design codes, independent checking and new bridge-building procedures were drawn up, but it was not soon enough to avert the worst disaster in iron bridge history

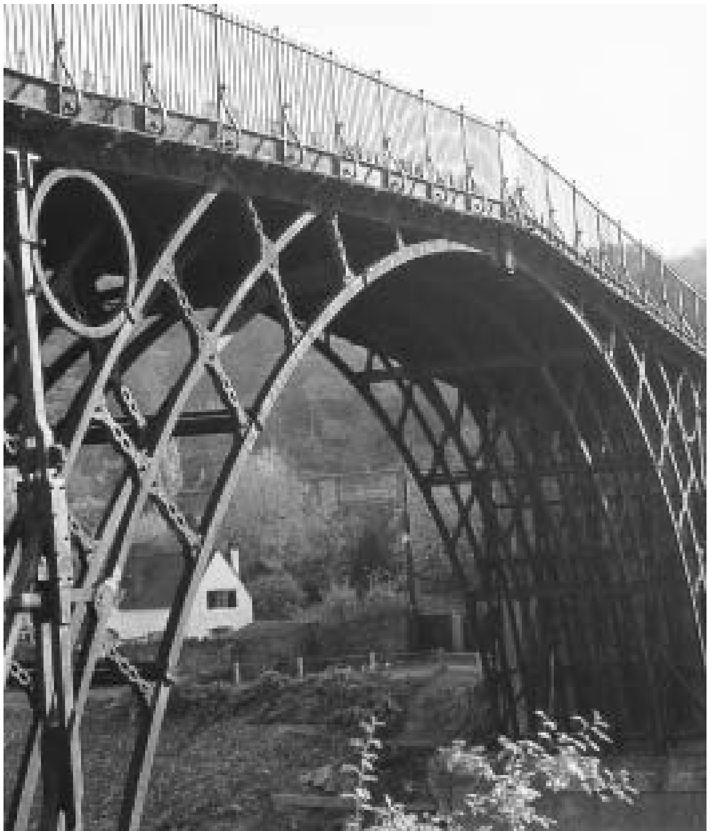

Figure 9 Iron Bridge in Coalbrookdale (courtesy of J Gill)

over the Tay estuary in 1878. It marked the end of the iron bridge.

Significant bridges

1779 Iron Bridge in Coalbrookdale, the first cast-iron bridge, designed as an arch structure by Pritchard for owner and builder Abraham Darby III (**Figure 9**).

1790 Buildwas Bridge, the second cast iron bridge built in Coalbrookdale, designed by Thomas Telford, used only half the weight of cast iron of the Iron Bridge.

1807 James Finlay builds first elemental suspension bridge – the Chain Bridge – in wrought iron in 1807 over the Potomac.

1821 Guinless Bridge, George Stephenson's wrought iron 'lentilcular' girder bridge for the Stockton to Darlington Railway.

1826 Menai Straits Bridge, famous eye bar, wrought iron chain suspension bridge over the Menai Straits, by Thomas Telford.

1834 The Fribourg Bridge, the world's longest iron suspension bridge.

1841 Whipple patents the cast iron 'bowstring' truss bridge.

Figure 10 Britannia Bridge, Anglesey

1846 Wheeling Suspension Bridge, Charles Ellet's record-breaking 1000 ft span, iron wire suspension bridge.

1850 Britannia Bridge, first box girder bridge concept, built in wrought iron by Robert Stephenson (**Figure 10**).

1853 Murphy designs a wrought iron Whipple truss, with pin connections.

1858 Royal Albert Bridge, Saltash, Brunel's famous tubular iron bridge, over the Tamar (**Figure 11**).

1876 The Ashtabula Bridge disaster in USA; 65 people die when this iron modified Howe truss collapses plunging a train and its passengers into the deep river gorge below.

1878 The Tay Bridge disaster, Dundee, Scotland where a passenger train with 75 people plunges into the Tay estuary, as the supporting wrought iron girders collapse in high winds.

The arrival of steel

Steel is a refined iron where carbon and other impurities are driven off. Techniques for making steel are said to have been known in China in 200 BC and in India in 500 BC. However, the process was very slow and laborious and after a great deal of time and energy only minute amounts were produced. It was very expensive, so it was only used for edging tools and weapons until the nineteenth century. In 1856, Henry Bessemer developed a process for bulk steel production by blowing air through molten iron to burn

Figure 11 Royal Albert Bridge, Saltash

off the impurities. It was followed by the open hearth method patented by Charles Siemens and Pierre Emile Martins in Birmingham, England in 1867, which is the basis for modern steel manufacture today. It took a while for steel to supersede iron, because it was expensive to manufacture. But when the world price of steel dropped by 75% in 1880, it suddenly was competitive with iron. It had vastly superior qualities, both in compression and tension; it was ductile and not brittle like iron, and was much stronger. It could be rolled, cast, or even drawn, to form rivets, wires, tubes and girders. The age of steel opened the door to tremendous advances in long-span bridge-building technology. The first bridges to exploit this new material were in the USA, where the steel arch, the steel truss and the wire rope suspension bridges were pioneered. Later, Britain led the world in the cantilever truss bridge and the steel box girder bridge deck.

The historical progress of the principle of building bridges in steel covering the period from 1880 to the present is described below.

The steel truss arch

When the steel prices dropped in the 1870s and 1880s the first important bridges to use steel were all in the USA. The arches of St Louis Bridge over the Mississippi and the five Whipple trusses of the Glasgow Bridge over the Missouri were the first to incorporate steel in truss construction. St Louis, situated on the Mississippi and near the confluence of the Missouri and Mississippi, was the most important town in mid-west USA, and the focal point of north–south river traffic and east–west overland routes.

1874 The St Louis Bridge, St Louis – James Eads builds the first triple-arch steel bridge.

1884 The Garabit Viaduct, St Flour, France – Gustav Eiffel's truss arch in wrought iron was the prototype for future steel truss construction. Eiffel would have preferred steel but chose wrought iron because it was more reliable in quality and cheaper.

1916 The Hell Gate Bridge, New York – the first 977 ft steel arch span in the world was designed by Gustav Lindenthal.

1931 The Bayonne Bridge, New York – the first bridge to be built with a cheaper carbon manganese steel, rather than nickel steel, and which is the composition of most modern steel.

1932 Sydney Harbour Bridge, Sydney – this famous steel arch was built using 50 000 tons of nickel steel. Its design was based on the Hell Gate Bridge.

1978 New River Gorge Bridge, West Virginia with a span of 518 m became the world's longest steel arch span until recently when two bridges in China have pushed their spans up to 552 m.

Figure 12 The Tyne Bridge, Newcastle upon Tyne

In the UK the Tyne Bridge, another steel truss arch structure, was built in the 1920s (see **Figure 12**).

The cantilever truss

Arch bridges had been constructed for many centuries in stone, then iron, and later, when it became available, in steel. Steel made it possible to build longer-span trusses than cast iron without any increase in the dead weight. Consequently it made cantilever long-span truss construction viable over wide estuaries. The first and most significant cantilever truss bridge to be built was the rail bridge over the Firth of Forth near Edinburgh, Scotland in 1890. The cantilever truss was rapidly adopted for the building of many US railroad bridges until the collapse of the Quebec Bridge in 1907 (**Figure 13**).

1886 The Fraser River Bridge, Canada – believed to be the first balanced cantilever truss bridge to be built. All the truss piers, links, and lower chord members were fabricated from Siemens–Martin steel. It was dismantled in 1910.

1890 The Forth Rail Bridge, Edinburgh, Scotland – the world's longest spanning bridge at 1700 ft, when it was finished.

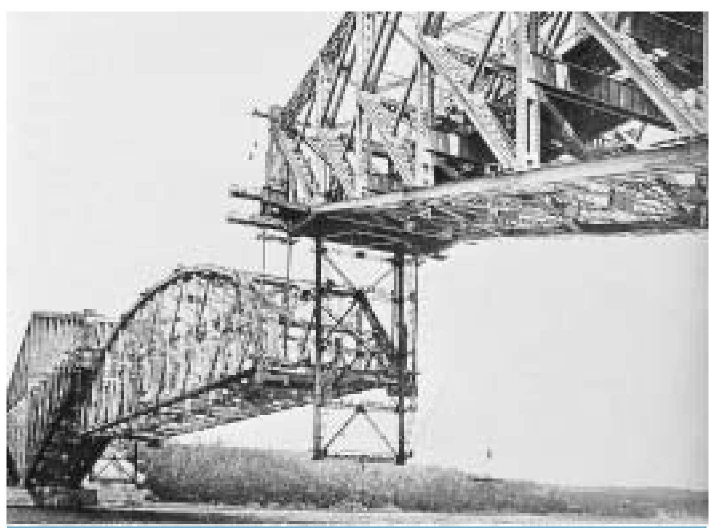

Figure 13 The Quebec Bridge, Canada

1891 The Cincinnatti Newport Bridge, Cincinnati – with its long through-cantilever spans and short truss spans, this was the prototype of many rail bridges in the USA.
1902 The Viaur Viaduct, France – this rail bridge between Toulouse and Lyons was an elegant variation of the balanced cantilever, with no suspended section between the two cantilever arms.
1917 The Quebec Bridge – completion of the second Quebec Bridge, the world's longest cantilever span.
1927 Carquinez Bridge – the last of the long cantilever truss bridges to be built in the USA although a second identical bridge was built alongside it in 1958 to increase traffic flow.

The suspension bridge

The early pioneers of chain suspension bridges were James Finlay, Thomas Telford, Samuel Brown and Marc Seguin, but they had only cast and wrought iron available in the building of their early suspension bridges. It was not until Charles Ellet's Wheeling Bridge had shown the potential of wire suspension using wrought iron that the concept was universally adopted. Undoubtedly the greatest exponent of early wire suspension construction and strand spinning technology was John Roebling. His Brooklyn Bridge was the first to use steel for the wires of suspension cables.

Suspension bridges are capable of huge spans, bridging wide river estuaries and deep valleys and have been essential in establishing road networks across a country. They have held the record for longest span from 1826 to the present day and only interrupted between 1890 to 1928, when the cantilever truss held the record.

1883 Brooklyn Bridge – following the completion of the Wheeling suspension bridge pioneered by Charles Ellet; John Roebling went on to design the Brooklyn Bridge, the first steel wire suspension bridge in the world.
1931 George Washington Bridge – the heaviest suspension bridge to use parallel wire cables rather than rope strand cable, and the longest span in the world for nearly a decade (**Figure 14**).
1950 Tacoma Narrows – the second Tacoma Narrows, rebuilt after the collapse of the first bridge with a deep stiffening truss deck, set the trend for future suspension bridge design in the USA.
1957 Mackinac – Big Mac is the longest overall suspension bridge in the USA.
1965 Verazzano Bridge – the last big suspension bridge to be built in the USA, also held the record for the longest span until 1981.
1967 Severn Bridge – the first bridge to have a slim, aerodynamic bridge deck, eliminating the need for deep stiffening trusses like those of US suspension bridges. It set the trend for future suspension bridge construction.

Figure 14 The George Washington Bridge, New York

1981 Humber Bridge – the longest span in the world when it was completed, with supporting strands that were inclined in a zig-zag fashion rather than the parallel arrangement preferred by the Americans.
1998 Great Belt, and the East Bridge – the Great Belt crossing is the longest bridge in Europe. For a short while the main span of the East Bridge held the record for the longest span in the world.
1998 Akashi Kaikyo – is one of a family of long-span bridges linking the islands of Honshu and Shikoku. Its main span of 1991 m makes it the longest span in the world.
2008 Messina Bridge, Italy – is planned with a main span of 3300 m, well beyond any other suspension bridge previously constructed.

Steel plate girder and box girder

Since the development of steel and of the I-beam, many beam bridges were built using a group of beams in parallel which were interconnected at the top to form a roadway. They were quick to assemble but they were only practical over relatively short spans for rail and road viaducts. The riveted girder I-beam was later superseded by the welded and friction grip bolted beam. However, relatively long spans were not efficient as the depth of the beam could become excessive. To counter this, web plate stiffeners were added at close intervals to prevent buckling of the beam. Another solution was to make the beam into a hollow box which was very rigid. In this way the depth of the beam could be reduced and material could be saved. The steel box girder beams could be quickly fabricated and were easy to transport. Their relatively shallow depth meant that high approaches were not necessary. Most of this pioneering work was carried out during and after the Second World War when there was a huge demand for fast and efficient bridge building for spans of up to 1000 ft. The major rebuilding programme in Germany witnessed the construction of many steel box girder and concrete box girder bridges in the 1950s and 1960s. For spans greater than 1000 ft the suspension and cable-stay bridge are generally more economical to construct.

In the 1970s the world's attention was focused on the collapse of steel box girder bridges under construction. The four bridges were in Vienna over the Danube, in Milford Haven in Wales (when four people were killed), a bridge over the Rhine in Germany and the West Gate Bridge in Melbourne over the Lower Yarra River. By far the worst collapse was on the West Gate Bridge, a single cable-stay structure with a continuous box girder deck. A deck span section 200 ft long and weighing 1200 tons, buckled and crashed off the pier support on to some site huts below, where workmen and engineers were having their lunch. Thirty-five people were killed in the tragedy. After this accident, further construction of steel box girder deck bridges was halted until better design standards, new site checking procedures and a fabrication specification were agreed internationally.

1936 Elbe Bridge – one of the early plate girder bridges on the German autobahn.
1948 Bonn Beuel – a later development of the plate girder into a flat arch, to reduce material weight.
1952 Cologne Deutz Bridge – first slender steel box girder bridge in the world.
1970s Failure of box girders at Milford Haven in Wales and West Gate Bridge in Australia halted further building of the steel box girder bridge decks for a time.

Concrete and the arch

Although engineers took a long time to realise the true potential of concrete as a building material, today it is used everywhere in a vast number of bridges and building applications. Concrete is a brittle material, like stone, good in compression, but not in tension, so if it starts to bend or twist it will crack. Concrete has to be reinforced with steel to give it ductility, so naturally its emergence followed the development of steel. In 1824 Joseph Aspdin made a crude cement from burning a mixture of clay and limestone at high temperature. The clinker that was formed was ground into a powder, and when this was mixed with water it reacted chemically to harden back into a rock. Cement is combined with sand, stones and water to create concrete, which remains fluid and plastic for a period of time, before it begins to set and hardens. It can be poured and placed into moulds or forms while it is fluid, to create bridge beams, arch spans, support piers – in fact a variety of structural shapes. This gives concrete special qualities as a material, and scope for bold and imaginative bridge ideas.

François Hennebique was the first to understand the theory and practical use of steel reinforcement in concrete, but it was Robert Maillart (1872–1940) who was first to pioneer and build bridges with reinforced concrete. Eugene Freysinnet, Maillart's contemporary, was also keen to experiment with concrete structures and went on to discover the art of prestressing and gave the bridge industry one of the most efficient methods of bridge deck construction in the world. Both these men were great engineers and champions of concrete bridges. What they achieved set the trend for future developments in concrete bridges – precast bridge beams, concrete arch, box girder and segmental cantilever construction. Concrete box girder bridge decks are incorporated in many modern cable-stay and suspension bridges.

Jean Muller and contractors Campenon Bernard were responsible for building the first match cast, glued segmental, concrete box girder bridge in the world. It is a technique that is used by many bridge builders across the world. The box girder span can be precast in segments or cast in place using a travelling formwork system. They can be built as balanced cantilevers each side of a pier or launched from one span to the next.

Concrete has been used in building most of the world's longest bridges. The relative cheapness of concrete compared to steel, the ability to rapidly precast or form prestressed beams of standard lengths, has made concrete economically attractive. Lake Ponchetrain Bridge, a precast concrete segmental box girder bridge in Louisiana is the longest bridge in the US with an overall length of 23 miles.

The concrete arch

1898 Glenfinnian Viaduct – the first concrete arch bridge to be built in England.
1905 Tavanasa Bridge – a breakthrough in the stiffened arch slab (**Figure 15**).
1922 St Pierre de Vouvray – early concrete bowstring arch of Freysinnet.

Figure 15 Tavanasa Bridge: a stiffened concrete arch bridge by Robert Maillart (courtesy of EH)

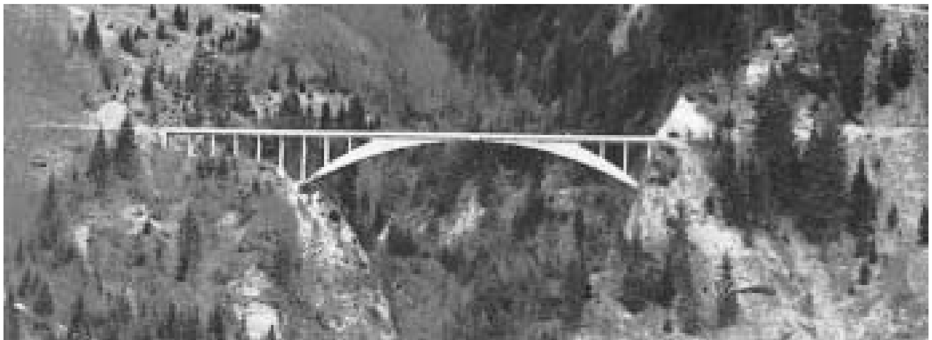

Figure 16 Salgina Gorge Bridge – one of the most aesthetic arch spans of Maillart (courtesy of EH)

1929 Plougastel Bridge – unique construction concept which used prestressing for the first time.
1930 Salgina Gorge Bridge – one of the most aesthetic arch spans of Maillart (**Figure 16**).
1936 Alsea Bay Bridge – completion of one of Conde McCullough's fine 'art deco' bridges in Oregon (demolished).
1964 Gladesville – use of precast prestressed segmental construction for the arch span.
1964 KRK (Croatia) – the longest concrete arch span in the world.

Concrete box girders

1950s–60s Many motorway bridges and viaducts were built in Europe and the USA using concrete box girder construction. Some were precast segmental construction, some were cast in place.
1952 Shelton Road Bridge – first match cast, glue segmental, box girder construction in the world developed by Jean Muller.
1956 Lake Ponchetrain Bridge – the second longest bridge in the world, is a precast segmental box girder bridge with 2700 spans and runs for 23 miles across Lake Ponchetrain near New Orleans. The second identical bridge, built alongside the original one in 1969, was 69 m longer.
1972 Medway Bridge – the first European river bridge to be built using concrete box girder construction (**Figure 17**).

Cable-stay bridges

Cable stays are an adaptation of the early rope bridges, and guy ropes for securing tent structures and the masts of sailing ships. When very rigid, trapezoidal box girder bridge decks were developed for suspension bridges, it allowed a single plane of stays to support the bridge deck directly. This meant that fewer cables were needed than for a conventional suspension system, there was no need for anchorages and therefore it was cheaper to construct. Cost and time have always been the principal motivators for change and innovation in bridge engineering.

The first modern cable-stay bridges were pioneered by German engineers just after the Second World War, led by Fritz Leonhardt, Rene Walter and Jörge Schlaich. The cable-stay bridge is probably the most visually pleasing of all modern long-span bridge forms. In recent times the development of the cable-stay and box girder bridge deck has continued with the work of Danish engineers COWI consult, bridge engineers Carlos Fernandez Casado of Spain, R. Greisch of Belgium, Jean Muller International, Sogelerg, and Michel Virloguex of France.

Cable stay history

1955 Störmstrund, Norway – the first cable-stay bridge.
1956 North Bridge, Dusseldorf – early harp arrangement for a family of cable-stay bridges over the Rhine. It was the prototype for many cable-stay bridges.
1959 Severins Bridge – the first to adopt an A-frame tower and the first bridge to use a fan configuration for the stays; a very efficient bridge form.
1962 Lake Maracaibo Bridge – an unusual composite cable-stay and concrete frame support structure for a bridge built in Venezuela, using local labour.
1962 Nordelbe Bridge, Hamburg – the first bridge to use a single plane of cables; the deck was a stiffened rectangular box girder.
1966 Wye Bridge, England – a single cable stay from the mast supports the continuous steel box girder bridge deck. Erskine Bridge built in 1971 was a better example of this construction.
1974 Brotonne Bridge – the first cable-stay bridge to use a precast concrete box girder deck and a single plane of cable stays (**Figure 18**).
1984 Coatzacoalcos II Bridge, Mexico – elegant pier and mast tower combining the rigidity of the A-frame with the economy of a single foundation.

Figure 17 The Medway Bridge, Kent

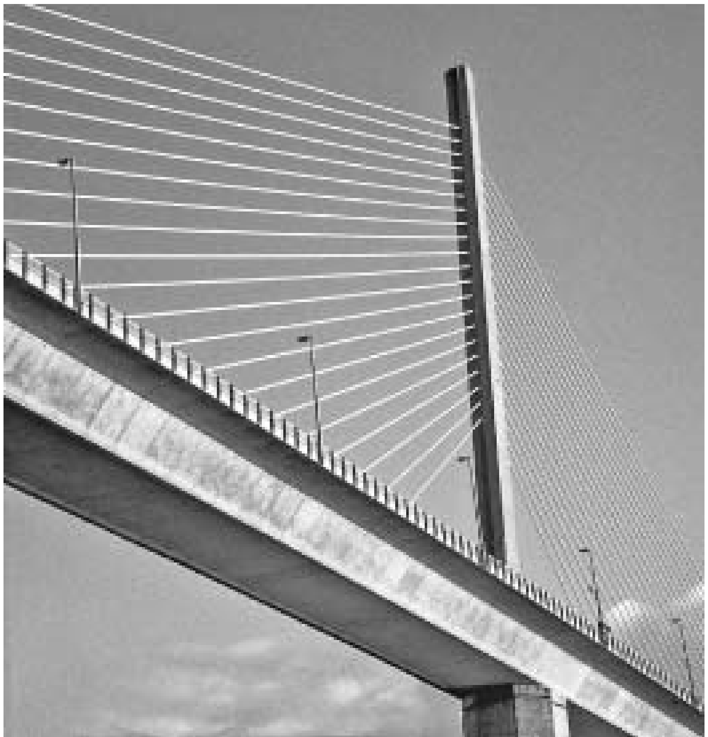

Figure 18 The Brotonne Bridge, Sotteville, France (courtesy of J Crossley)

1995 Pont de Normandie – breakthrough in the design of very long cable-stay spans.
2008 Sutong Bridge, China – pushes cable-stayed clear span beyond 1000 m.

Aesthetic design in bridges

Introduction

Is it possible there is a universal law or truth about beauty on which we can all agree? We can probably argue that no matter what our aesthetic taste in art, literature or music, certain works have been universally acclaimed as masterpieces because they please the senses, evoke admiration and a feeling of well-being. Music, literature and painting can appeal to an audience directly, unlike a building or bridge whose beauty has to be 'read' through its structural form, which has been designed to serve another more fundamental purpose. Judging what is great from many competent examples must come from an individual's own experience and understanding of past and contemporary styles of expression. The desire to please or to shock is not fundamental in the design of bridges whose primary purpose is to provide a safe passage over an obstacle, be it a river or gorge or another roadway. A bridge taken in it purest sense is no more than an extension of a pathway, a roadway or a canal. We do not regard roads, paths and canals as 'art forms' that evoke aesthetic pleasure as we do with buildings. Hence, it is reasonable to ask why should a bridge be an art form? In the very early years of civilisation, bridges were built to breach a chasm or stream to satisfy just that purpose. They had no aesthetic function. Later on when great civilisations placed a temporal value on the quality of their buildings and heightened their religious and cultural beliefs through their architecture, these values transferred to bridges. And like all the important buildings of a period, when stone and timber were the principal sources of construction material, work was done by skilled craftsmen. Masons would cut, chisel and hew stones; carpenters would saw, plane and connect pieces of timber falsework or centring to support the masonry structure. It took many years to 'fashion' a bridge. Each stone was carefully cut to fit precisely into position. Hundreds of stone masons would be employed to work on the important bridges. Voussoirs and key stones were sculptured and tooled in the architectural style of the period. Architecture was regarded as an integral part of bridge construction and this tradition continued into the age of iron, where highly decorative wrought iron and cast iron sections were expressed on the external faces of the bridge. Well into the middle of the twentieth century arch bridges in concrete and steel were cloaked in masonry panels to imitate the Renaissance, Classical and Baroque periods.

Gradually, however, as the pace of industrial change intensified, by the expansion of the railways, and by the building of road networks, a radical step change in the design and construction of bridges occurred. Bridges had to be functional, they had to be quick to build, low in cost, and structurally efficient. They had to span further and use fewer materials in construction. Less excavation for deep piers and foundations under water meant faster construction, whereas short continuous trestle supports across a wide valley were simple to construct and required shallow foundations. Under these pressures, standardisation and prefabrication of bridges displaced aesthetic consideration in bridge design. Of course, there were exceptions when prestigious bridges were commissioned in major commercial centres to retain the quality and character of the built environment. And sometimes even these considerations were sidelined in the name of progress and regeneration, as was the case in the aftermath of the two world wars. When economic stability returns to a nation after the ravages of war, and living standards start to rise, so does interest in the arts and quality of the built environment.

After the Second World War, for example, rebuilding activity had to be fast and efficient, with great emphasis placed on prefabrication, system-built housing and the tower block to rehouse as many people as possible. In Germany, rebuilding the many bridges that were demolished led to the development of the plate girder and box girder structure. Box girder bridge structures with standardised sections, proliferated the road network and motorways of Europe, over viaducts, interchanges, flyovers and river crossings. In this period the shape and form of the bridge was dictated by the contractor's preference for repetition and simplicity of construction.

Given this history it is hardly surprising to find that many of our towns and urban areas and motorway network are blighted by ugly, functional bridging structures whose presence now causes a public outcry.

Figure 19 An example of Fritz Leonhardt's work – Maintelbrücke Gamunden Bridge (courtesy of F Leonhardt)

Bridge aesthetics in the twentieth century

Over the centuries as the various forms of bridges evolved in the major towns and cities, the architectural style of the period was superimposed on them, to create order and homogeneity. Classical, Romanesque, Byzantine, Islamic, Renaissance, Gothic, Baroque, Georgian and Victorian architectural styles adorn many historic bridges today, such as the Renaissance Rialto Bridge in Venice, the Romanesque Pont Saint Angelo in Rome, the French Gothic of the Pont de la Concorde in Paris. They are recognisable symbols of an era, of imperialist ambition and nationhood, where the dominant form of construction was the arch. But with the arrival of steel and concrete in the early part of the twentieth century, new structural forms emerged in building and bridge design that radically changed both the architecture and visual expression of bridges. The segmental arch was replaced by the flat arch, the flat plate girder and box girder beam; the cantilever truss was replaced by the cable stay and the suspension bridge. The decorative stone-clad bridges of the past were slowly replaced by the minimalism of highly engineered structures.

Undoubtedly, during the period from the 1920s to the 1940s the greatest concentration of bridge building was in the USA. It was in step with the massive industrial and commercial expansion throughout the country, and emergence of the high-rise building – the skyscraper. And in building bridges – the great suspension, steel arch and cantilever truss bridges – those that were important were the subject of much debate about appearance, and harmony with their surrounding environment. Champions of aesthetic bridge design emerged – David Steinman, Condo McCullough, Gustav Lindenthal and Othmar Ammann. All of them were engineers. Steinman was the most flamboyant and outspoken individual among this group and wrote books and articles on the subject. Condo McCullough's 'art deco' bridges – inspired by the bridges of Robert Maillart – were aesthetic masterpieces of the concrete arch and steel cantilever truss bridge.

In the 1950s and 1960s the bridge building boom moved to Europe following the war years, with a plethora of utilitarian structures built in the name of economy. Architectural and aesthetic considerations were reduced to a minor role. Bland, insensitive and crude bridge structures and viaducts appeared across the open countryside, and through towns and across cities. Concern about the impact these bridges would have on the built environment brought Fritz Leonhardt, one of Germany's leading bridge engineers, to Berlin in the 1950s. He was part of a small team who the government highways department made responsible for incorporating aesthetics into bridge design. He worked with a number of leading German architects, particularly Paul Bonatz, and through this association and from extensive field studies of bridges, he evolved a set of criteria on the design of good-looking bridges. He set this out in his book on bridge aesthetics *Brucken* (*Bridges*). **Figure 19** shows an example of one of his bridges.

Although bridge design was dominated by civil engineers in the twentieth century, somehow the aesthetic vision of the early pioneers' such as Roebling, Eiffel and Maillart and later by Steinman and McCullough *et al.*, was never seriously addressed in contemporary bridge design in the UK during the middle to later half of the twentieth century. It appears that the education and training of British civil engineers did not include an understanding on the architecture of the built environment.

Was this also true in other parts of Europe after the war? It is possible that in France, with the emergence of bridges such as Plougastel (**Figure 20**), Orly Airport Viaduct, Tan Carville and Brotonne and more recently examples such as the Pont Isère (**Figure 21**), the second Garabit Viaduct and Pont de Normandie, a conscious effort was made to build beautiful bridges. In conversation with Jean Muller and Michel Virloguex, comparing their educational background and training with that of the great Eugene Freyssinet, it would seem that all of them had some education and teaching on bridge aesthetics at university. It might explain why their bridges look elegant and thoroughly well engineered. It also appears that senior personnel in government bridge departments in France who appoint consultants and commission the building of the major bridges, have the same commitment to build visually pleasing bridge structures. Many of them have been schooled in

Figure 20 Plougastel, France (courtesy of JMI)

bridge engineering at the University of Paris. Awareness of bridge aesthetics at engineering school is a critical factor. And having developed a design which fully reconciles aesthetics, it is then sent out for tendering. Contractors in France are not given the opportunity to propose cheaper alternative designs, only the opportunity to propose construction innovations in building the chosen design economically. Not surprisingly, aesthetically designed bridges are competitive on price, as the major constructors in France over the years have invested in new technology and sophisticated erection techniques to build efficiently.

In England in the 1990s two unconnected, yet controversial, events marked a watershed in bridge aesthetics and gave recognition to the role of architects in bridge design. The first of these events was 'Bloomers Hole Bridge' competition run by the Royal Fine Arts Commission (RFAC) on behalf of the District Council of Thamesdown. The competition, which was run on RIBA rules, was open to anyone – bridge engineers, architects, civil engineers and so on. The entrants had to submit an artistic impression of the bridge and accompany it with notes explaining its construction, how it would be built and describing its special qualities for the location. The bridge was to be a new pedestrian crossing over the upper reaches of the Thames in a very unspoilt setting in Lechlade. Each entrant was given a reference number, so that the judges had no knowledge of the name of the entrant. The winning design, out of 300 entries, was created by an architect. The president of the RFAC, speaking on behalf of the judging panel, described the winning design as a 'beautiful solution of great simplicity and elegance entirely appropriate to its rural setting' – but it was not built. The residents of Lechlade labelled the design a 'yuppie tennis racket from hell' and planning permission was withheld. Nevertheless, the imaginative design ideas that resulted from this competition prompted many local authorities and development corporations,

Figure 21 Pont Isère, Romans, France (courtesy of NCE/Grant Smith)

particularly the London Docklands Development Corporation (LDDC), to follow suit. Coincident with the competition was the second watershed event – a design study for the proposed East London River Crossing by Santiago Calatrava that took the bridge world by storm. Calatrava's dramatic, rapier-slim bridge concept arching over the Thames showed how a well-engineered bridge design can produce a pleasing aesthetic – it seemed that everyone wanted Calatrava to design a bridge for them.

During the past three decades in the UK, architectural style has been a confusing cocktail of past and present influences, high-tech and neo-classical, romantic modernism and minimalism which has in some ways marginalised the influence and appreciation of architecture. As a result, highway authorities that commission bridges have paid more attention to structural efficiency, cost control and long-term durability. Aesthetic consideration, if addressed at all, was treated as an appendage, and the first item to be dropped if the tender price was high. The reason for this was simple: both the client and design consultant were civil engineers with little empathy towards modern architecture and the aesthetic judgement of architects on bridge design. Unfortunately earlier this decade a recent exhibition on 'living bridges' at the Royal Academy has confirmed this point of view. The architecture-inspired ideas tended to make bridges look and function like buildings . . . and failed. But despite this setback the 'old school' attitudes of civil and bridge engineers are slowly being replaced by a new generation of engineers and clients who have recognised the value of working with architects.

The search for aesthetic understanding

Why have architecture and bridge engineering not found a common language over the centuries as has happened in building structures? There have been periods of bridge building when both ideals were combined in bridges. Engineers such as Lindenthal, Ammann, Steinman (**Figure 22**) and McCullough in the USA were advocates of visually pleasing bridges. In Europe individuals such as Freysinnet, Maillart, Leonhardt, Menn, Muller and Caltrava and consultant groups such as Arup, Cowi and Cassado were recognised for their aesthetic design of bridges. All of them will own up to the fact that they employed or worked alongside architects. Ammann worked closely with Cass Gilbert, the architect of the gothic Woolworth Tower, arguably the most beautiful skyscraper ever built. Steinman built many great bridges, and tried hard to add flair and style to his designs, but he had to teach himself aesthetics at university. 'In my student days when we were taught bridge design, I never heard the word ''beauty'' mentioned once. We concentrated on stress analysis, design formulae and graphic methods, strength of materials, locomotive loading and influence lines, pin connections, gusset plates and lattice bars, estimating, fabrication and erection and so on . . . But not a word was said about artistic design, about the aesthetic considerations in the design of engineering structures. And there was no whisper of thought that bridges could be beautiful' writes Steinman in an article on the beauty of bridges that appeared in the *Hudson Engineering Journal*. So how did Steinman learn to develop his skill in aesthetic design? 'For my graduation thesis in 1908 at Columbia University I chose to design the Henry Hudson Memorial Bridge [**Figure 23**] as a steel arch. I worked on the idea for a year

Figure 22 David Steinman (courtesy of Steinman Consulting)

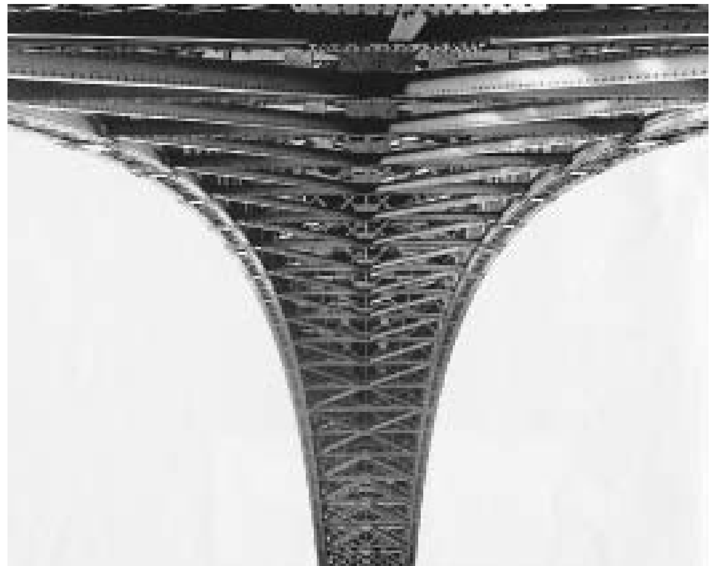

Figure 23 Henry Hudson Memorial Bridge, New York (courtesy of Steinman Consulting)

and a half before my graduation. I was determined to make this design a model of technical and analytical excellence. But this was not all . . . I was further determined to make my design a model of artistic excellence.' Steinman read everything he could on the subject of beauty, and aesthetics in design. He discussed the subject with friends who were studying architecture, but they could not help him much. 'They were trained in masonry architecture, in classic orders, ornamentation and mouldings . . . steel was an unfamiliar material.' Instead, he visited existing bridges, to observe and reason why some were ugly and others were thrilling to look at. He spent a lot of time climbing and walking over the Washington Arch Bridge, to study its design from every artistic angle because it inspired him. 'In my thesis I included a thorough discussion and analysis of the artistic merits of my design. When I finished the thesis and turned it over to Professor William Burr . . . he gave me the unusual mark of 100 per cent.' **Figure 24** shows another of Steinman's bridges – St John's Bridge in Portland, Oregon – which was opened by Steinman in 1931.

In the eighteenth century Perronet took exception to any design that was not pleasing to the eye. In discussing the Nogent Bridge on the upper Seine, he remarked 'some engineers, finding that the arches . . . do not rise enough near the springing, have given a large number of degrees and a larger radius to this part of the curve . . . but such curves have a fault disagreeable to the eye'. The proportions, the visual line and aesthetic of the arch were important factors in Perronet's mind. He was trained as an architect. Pont Neuilly built over the Seine in Paris in 1776 was one of the most admired bridges in architecture. James Finch, author of *Engineering and Western Civilisation*, called Nueilly 'the most graceful and beautiful stone

Figure 24 St John's Bridge, Portland, Oregon (courtesy of Steinman Consulting)

bridge ever built'. Sadly it was demolished in 1956 to make way for a new steel arch bridge. It would have been useful to have studied Nueilly today, but one has to recognise that the stone arch is an obsolete technology and has been replaced by the cable-stay, steel arch and concrete box girder bridge.

In the 1960s Leonhardt suggested the use of the Greek 'golden section' to solve the problem of 'good order' and harmony of proportions. He blames the lack of education for the poor understanding of the importance of aesthetics. There is too much emphasis placed on material economy and that is why there are so many ugly structures. 'The whole of society, especially the public authority, the owner builders, the cost consultants and clients are just as much to blame as the engineers and architects' argues Leonhardt. In his search for an explanation on good aesthetics he referred to the work of Vitruvius and Palladio and believed that in architecture the idea of good proportion, order and harmony is very appropriate in bridge design. Many engineers have regarded his book *Brucken* as the definitive guide to bridge aesthetics, but the majority may not have fully appreciated the moral, philosophical and esoteric arguments that he explored. The section on the origins of the golden mean and golden section will generally appeal to the more numerate engineers, who are used to working with mathematical formulae to find solutions.

The Greek philosophers tried to define aesthetic beauty through geometric proportion after years of study and observation. The suggestion was that a line should be divided so that the longer part is to the short part as the longer part is to the whole. The resulting section was known as the golden section and was roughly divided into irrational ratios of 5:8, 8:13, 13:21 and so on. The ratios must never be exact multiples.

It is a dangerous precedent to set, as the golden section can be applied to a bridge just as deflection or stress calculations are done. What Leonhardt concluded in his book, after considering how aesthetics in design were assimilated in both buildings and bridges, was that aesthetics could only be learnt by practice and by the study of attractive bridges. He warned that designers must not assume that the simple application of rules on good design will in itself lead to beautiful bridges. He recommends that models are made of the bridge to visualise the whole design in order to appraise its aesthetic values. Ethics and morality play a part in good design according to Leonhardt. Perhaps the words that he was searching for were integrity and purity of form. There has been a tendency to design gigantic and egotistic statements for bridge structures out of the vanity and ambition of the client. The recent competition for Poole Harbour Bridge was a case in point. It may never be built because of its high cost and because of its lack of integration into the local community it must also serve. One solution that was modest in ambition, but was high on community value, with small shops, houses and light industrial buildings built along the length of a new causeway, was entirely appropriate, but alas it was not designed as a 'gateway' structure and did not win.

Jon Wallsgrove of the Highways Agency in the UK suggests that the proportions of a bridge – the relationship of the parts to each other and to the whole – could be distilled down to the number seven. He made this observation after researching many books written on aesthetics and beauty over the centuries. The reason for this is that the brain apparently can recognise ratios and objects up to a maximum of seven without counting. He suggests that the ratio of say the span to the height of a bridge, or the span to overall length for example, should not exceed seven – for example 1:7; 2:3; 1:2:4 and so on. When the proportions are less than seven they are instantly recognised and appear right and beautiful. The use of shadow line, edge cantilevers and modelling of the surface of the bridge can improve the aesthetic proportion by reducing the visual line of the depth or width of a section, since the eye will measure the strongest visual line of the section, not the actual structural edge.

Fred Gottemoeller – a bridge engineer and architect – concurs with the view that in the USA today aesthetics in bridge design has largely been ignored by the bridge profession and client body. In his book *Bridgescape*, Gottemoeller sums up the dilemma facing many bridge engineers on the question of aesthetics: 'Aesthetics is a mysterious subject to most engineers, not lending itself to the engineer's usual tools of analysis, and rarely taught in engineering schools. Being both an architect and engineer, I know that it is possible to demystify the subject in the mind of the engineer. The work of Maillart, Muller, Menn and others prove that engineers can understand aesthetics. Unfortunately such examples are too rare. The principle of bridge aesthetics should be made accessible to all engineers.' Gottemoeller has written a clearsighted, practical book on good bridge design, in a style and language that should appeal to any literate bridge engineer. It is not a book full of pretty reference pictures – the ideas have to work on the intellect through personal research.

It may take time before the new generation of bridge engineers with greater awareness and sensitivity of bridge aesthetics will soften attitudes towards working with architects out of choice. It is doubtful that the basic training and education of civil engineers will change very much in the coming decade. Many academics will feel there is no need for aesthetics to be included in a degree course and that it should be something an individual should learn in practice. Like it or not, those that are attracted to bridge design and civil engineering do so because they have good analytical and numerate skills. It is pointless putting a paintbrush in the hands of someone who hates painting and then expect them to awaken to aesthetic appreciation. In general, the undergraduate engineer has taken the civil engineering option because calculus is preferred to essay writing, technical drawing to abstract art, and scientific experiment to an appraisal of a Thomas Hardy novel. Encouragement in the visual arts and aesthetics will come with practice, and from working alongside architects who are more able to sketch ideas on paper, model the outline of bridge shapes and look for the visible clues to see if a scheme fits well with the surrounding landscape. Architects can help with aesthetic proportion – of structural depth-to-span length, pier shape and spacing, the detailing of the abutment structure, the colour and texture of the finished surface of a bridge, and the preparation of scale models. After all, they have been trained to do this.

The growing trend today is to appoint a team of designers from partnerships between engineers and architects to ensure that aesthetics in design is fully considered. This is a healthy sign. The LDDC successfully forged partnerships between architects and engineers in the design of a series of innovative and creative footbridges that are sited in London's Docklands. Architects such as the Percy Thomas Partnership, Sir Norman Foster & Partners, Leifschutz Davidson and Chris Wilkinson in particular, have made the transfer from building architecture to bridge architecture effortlessly. In France, the architect Alain Speilman has specialised in bridge architecture for nearly 30 years, and has worked with many of France's leading bridge consultants and been involved in the design of over 40 bridge schemes. He is following a tradition in France, where architects such as Arsac and Lavigne have worked closely with bridge engineers. Without doubt the most significant bridge project of the decade, the Millau Viaduct in central France, which was won in competition by architect Sir Norman Foster & Partners and a team of leading French bridge designers has redefined the role of the architect and bridge engineer for the future.

Each period in history will no doubt uncover monsters and marvels of bridge engineering, as they have done with buildings. Succeeding generations can learn to distinguish between good and bad design. What is an example of bad design? We may look on Tower Bridge today as a wonderful, monumental structure, the gateway into the Pool of London, but as a bridge it is ostentatious, with grossly exaggerated towers for such a short span. Some might regard it as a building with a drawbridge, but as a building it serves no real function other than to glorify the might of the British Empire. It would have made more sense to have built two great towers rising out of the water some way upstream of an elegant bridge, located where the bridge is now sited. And if individuals care about the quality of architecture of the built environment, they should voice their opinion and express their views on good and bad design. Silent disapproval is no better than bored indifference. It's worth reflecting that when Tower Bridge was being designed, the Garabit Viaduct and the Brooklyn Bridge had been built. Both bridges and their famous designers were to inspire the engineering world for many decades, but alas not the Victorians.

Civic pride has over the centuries compelled governments and local highway authorities to attempt to build pleasing bridges in our cities and important towns in order to maintain the quality of the built environment. We all agree that the linking of places via bridges symbolises cooperation, communication and continuity and that the bridge is one of the most important structures to be built. It is the modest span bridges over motorways, across canals and waterways in built-up urban areas that are most devoid of any sensitivity with their surroundings – the built environment and the urban fabric of our community. These featureless structures are in such profusion – plate girder bridge decks carrying trains over a busy high street and dirt-stained urban motorway overbridges – that they are the only bridges most of us see as we journey through a town or a city. The cause of this blight stems largely from legislative doctrine on bridge design imposed by highway authorities, whose remit is to ensure that the design conforms to a set of rules on how it should perform and how little it will cost. It encourages the mediocre, the mundane and unimaginative design to be passed as 'fit for purpose'. What can be done to improve things? The way forward has already been shown by the footbridges commissioned by LDDC in the UK, by the bridges built by Caltrans